EFFECT OF CURRENT VARIATIONS ON MATERIAL PROPERTIES AND THERMAL STRESSES IN SØDERBERG ELECTRODES

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A safe Søderberg electrode performance is possible to obtain by keeping stable operational conditions - the continuous electrode system. However, from time to time, a state of unsteady conditions will occur. After a long furnace shut-down, breakage of the baked electrode may take place. This is explained by great temperature changes, developing high thermal stresses.

A high current density before shut-down will increase the tendency for a hard breakage, while a favourable stop procedure reduces the stresses. On the other hand, it is also experienced that breakages can occur in connection with relatively low current and short furnace stops, if the current fluctuates or the shut-downs are repeated.

The properties of the electrode materials will change in a Søderberg electrode as the temperatures increase downwards in the furnace. In particular, it should be noted that the mechanical strength decreases towards 2000°C, representing a critical area regarding electrode breakages. During a cooling period the materials will become even weaker, but mainly gaining their strength by reheating, (as after a shutdown). Other material properties will also change.

Existing mathematical models , developed by Elkem, have been used to simulate the above conditions - the current variations with changing material properties. A comparison of the computed thermal stresses with the measured material strength explains possible breakages. Material tests and mechanisms at elevated temperatures are presented.

INTRODUCTION

The purpose of the Søderberg electrode system is to conduct high electric current into reduction furnaces. It should, however, be noted that the current is also determining the "electrode production" itself - the self-baking electrode - as well as the success of electrode operation.

Experience with Søderberg electrodes shows that optimal performance is obtained by keeping constant conditions within recommended specifications. The continuous electrode system should be aimed at by:

- charging a proper carbon paste at short time intervals
- using a reliable design and equipment
- maintaining stable operational conditions

The latter includes electrodes with constant current load, an advantage for the operation of the smelting furnace as well as the electrode itself.

This paper summarizes our opinion concerning the importance of a continuous electrode operation. However, since this is impossible in reality, the present work concentrates on the effect of current variations in regard to electrode performance and not that of the smelting process. The electrode current, a very important parameter, will strongly affect the electrode temperatures, thermal stresses and material properties. The work is based on:

- Theoretical studies - mainly the application of mathematical models developed for the Søderberg electrodes. These are simulating variations in the electrode current, while electrode paste and equipment are considered to be of a good and constant quality. Thermal stresses are calculated in an electrode of diameter 1.7 meter in an open furnace used for the production of ferrosilicon.
- Laboratory measurements - which have been carried out on carbon materials for the determination of the material strength and other properties as a function of temperature. The tests have been performed at temperatures up to 2000°C.

ELECTRODE PARAMETERS

Some comments about the main electrode parameters, important for a continuous operation, are valuable in order to get a better understanding of the complex electrode system:

- The current enters the electrode casing from the contact clamps and is further distributed to the carbon materials. Furnace shut-downs or other changes in electrode current develop unwanted temperature gradients and corresponding thermal stresses, which may lead to cracks in the baked electrode materials. This may occur quite frequently, making "hard breakages" the most common electrode problem in many furnaces. Current variations will also strongly influence the very important baking process. More details about the importance of electrode current are followed up in this paper.
- The slipping rate is another extremely important electrode parameter, which is closely connected with electrode consumption. The baking of paste in the holder region should be a constant process in order to take care of material shrinkage/expansion, as well as gas evolution and diffusion from the paste binder. In this way, the baked electrode should obtain a good quality. A slipping in small increments is necessary in order to avoid "soft breakages" in the paste, often the most serious type of electrode problems. This may be the case if the slipping rate is relatively high when compared to current/heat generation. A possible long slipping of the electrode, for example 1 to 2 meters, results in a poor carbon quality owing to the discontinuous baking process.
- The electrode movement in the furnace is performed in relation to the slipping rate, although it is also adjusted in accordance with the position of the electrode tip and the metallurgical conditions in the furnace process zone. Normally, the movement will have considerably less effect than reasonable changes in current and slipping.
- The steel casings in the upper part of the electrode should be properly welded together. In order to maintain a continuous electrode column, the fins in the casing sections should also be welded in the joints, without fin overlapping.
- The softening of carbon paste depends on temperature and pressure. A regular charging - at least once a day - should be the rule. Local overheating of the soft paste should be avoided. It is important to maintain the original grain composition of the soft paste. Segregated materials may give problems during the baking and result in an inferior quality of the baked electrode.

Other factors affecting electrode operation are dependent on the design and construction of the electrode itself, as well as the electrode installation/position in the furnace pot. Axisymmetrical conditions will normally not occur due to the following items:

- The electrode holder is a complex construction of electrical and mechanical components. The current from the transformers should be evenly distributed to the contact clamps and a correct contact pressure on the clamps will control the electrical resistance between clamps and casing. Both of the factors are important for heat dissipation in the holder area.
- The adjacent electrodes will normally influence the temperature surroundings of an electrode and give a hotter material towards the furnace center.
- The proximity effect is a similar distortion of the electrode current, while the skin effect, the concentration of electric current near to the surface, will be significant in large electrodes, but in the radial direction only.

The described parameters are all connected, or will influence each other in one way or another. This should be kept in mind even if this paper comprises the electrode current only.

ELECTRODE CURRENT

The current is conducted in the copper bus tubes from the transformers to the contact clamps in the holder region. Current then passes into the electrode itself via the steel casing and fins, and gradually transforms the carbon into an electrical conductor of high strength. The purpose of the electrode, to conduct a large amount of current into the process zone, is thus possible.

Firstly, Fig. 1 illustrates the current transfer from the contact clamps to the casing. The "electrode current" curve indicates that during the current transfer the main part enters the electrode from the lower part of the clamps. A "normal", relatively low contact resistance is used. The linear values vary from $2.9 \cdot 10^{-4}$ to $1.6 \cdot 10^{-5}$ ohm m^2 at the top and the lower holder end, respectively. Higher values give a more even current distribution.

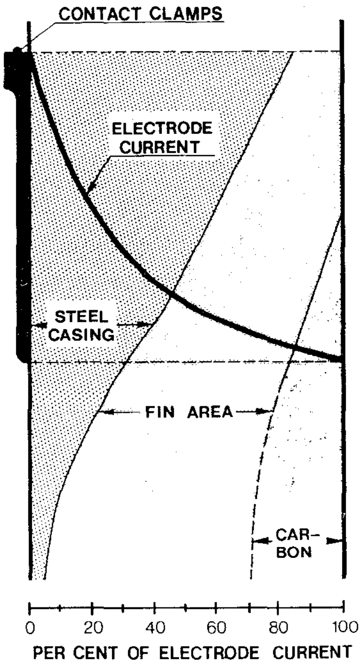

Fig. 1. Current transfer and distribution in the holder region.

Fig. 1 also shows current distribution in the holder region and further down in the electrode. The amount of current conducted by the outer steel casing, until the steel burns away, is indicated. Furthermore, the current in the electrode cross-section consisting of the steel fins and adjacent carbon, as well as the current conducted by the carbon alone, is illustrated. When the steel has disappeared completely, the carbon will conduct all the current. The results are drawn from calculations using a two-dimensional electrode model (1). In addition to contact resistance, the distribution depends on the current load, electrode temperatures and material properties (casing design, paste quality).

In order to optimize the furnace production, a highest possible current load, limited by the transformer capacity only, is desirable and often used. However, the electrode itself and the electrode equipment also have limits:

- A higher current load will increase heat generation, temperatures, and the tendency for thermal stresses during furnace shut-downs.
- By increasing the current (and surrounding temperatures), the load on electrode equipment, such as bus tubes and holder components, will be higher. There will be an increasing tendency for critical shut-downs, in many cases combined with water leakages.

Recommended ranges for the current capacity of Søderberg electrodes are given in order to secure a safe operation. Normally, the production of FeSi and CaC_2 will require the highest load. For an electrode diameter of 1.7 meter, Elkem will normally recommend up to 130 kA (current density 5.7 A/cm^2). Nevertheless, electrodes may even be operated above this range. During continuous operation - steady state - such a high load will normally not cause any problems, but during shut-downs high thermal stresses may occur. These conditions will be discussed.

When electrode current is varied, the following important aspect should be kept in mind. The electric resistance (R) in an electrode may be regarded more or less constant, and the heat generation (W) will be proportional to the square of the electrode current (I), i.e. $W = RI^2$. This means that when operating with a normal current load, any relatively small current fluctuations will have a considerable effect on the heat conditions in the electrode. Compared with this heat, operating with low current values in connection with shut-downs will have minor influence, even during considerably current variations.

The importance of current on the whole electrode performance will be discussed below. Firstly, heat balances for the electrode at various levels of the current will be shown. These are closely related to temperature distributions, which again will influence the material quality and the thermal stresses.

To acquire information about the current paths in an electrode system is important. However, a complete distribution of alternating current in an operating electrode is impossible to measure. Temperature recording is easier, even at relatively high temperatures. Recorded data have been used to verify computations with electrode models, which are very important tools in electrode studies. The following models developed for the Søderberg electrode have been used in this report:

- Two-dimensional static model, ELKEM X, mainly for calculating current and temperature distribution (1).
- Three-dimensional static model, ELKEM 3X, for calculating current and temperature distribution (2).
- Two-dimensional dynamic model, ELKEM D, for calculating temperatures when the electrode parameters are varied as a function of time. Transient current conditions are simulated (3).
- Two-dimensional strength model, ELKEM T, for calculating thermal stresses in the baked electrode in accordance with temperatures from the dynamic computations (4).

HEAT BALANCES / TEMPERATURE DISTRIBUTIONS

Fig. 2 shows the heat balances of an electrode computed with the ELKEM X model. The normal current for a 1.7 meter diameter electrode is, in Case A, 130 kA. In two other calculations the current is changed to 100 kA and 150 kA. The current is the only change of input data from one case to the next.

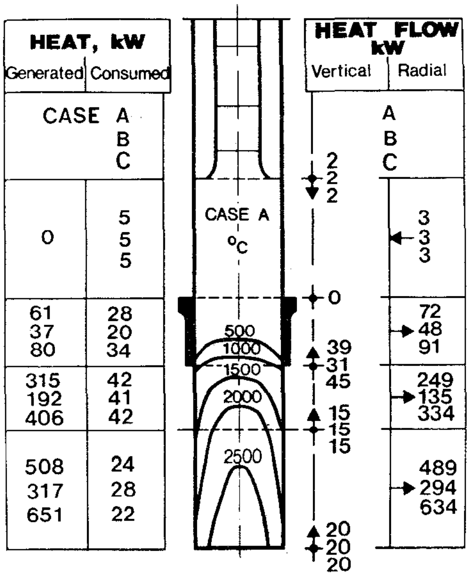

Fig. 2. Heat balances and temperature distribution. Case A 130 kA, Case B 100 kA, Case C 150 kA.

In the calculations the electrode is divided into several zones; in these three cases four zones in the longitudinal direction (which are again divided into smaller computational points). The zones depend primarily on the boundary conditions. The following comments can be made:

- The electric current generates the major part of the energy, which takes place in the holder region and downwards in the electrode. Totally, the current in Case A generates as much as 884 kW inside the electrode, plus another 375 kW owing to the contact resistance between the contact clamps and the electrode. The latter is, however, immediately absorbed by the water-cooled clamps and is not included in the balance. A change in the current supply will strongly influence the amount of generated heat, as seen by comparison of the three cases in the figure.
- The heat consumed in the electrode is also presented in Fig. 2. The amount necessary for heating the electrode materials is relatively small. The minimal part required to heat and melt the charged paste is transferred from the surroundings.
- The vertical heat flow is also small, as demonstrated by the calculations. Its maximum value is reached at the lower end of the clamps.
- The radial heat flow is therefore a considerable contribution to balance with the heat generation. This heat leaves the electrode surface mainly by radiation to the charged materials or into the air.

The heat balance for an electrode is, as shown, for the most part determined by the electrode current. A more direct demonstration of the current effect can be performed by using the temperature profiles. A good electrode performance can only be obtained if the temperature distribution is under control.

Fig. 2 includes a simplified temperature distribution for Case A with 130 kA. Fig. 3 focuses on the effect of current variations on the temperatures in the holder region of the same electrode. The results correspond to the determination of the heat balances. By normal operational conditions, with 130 kA as input, the baking zone - defined as the 500°C isotherm - is stabilized within the lower part of the holder.

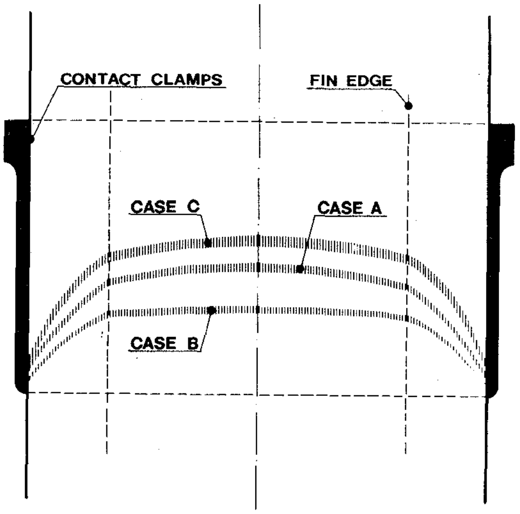

Fig. 3. Baking zone position. Case A 130 kA, Case B 100 kA, Case C 150 kA

An increase of the current to 150 kA (Case C) will raise the profile somewhat, especially towards the center, but operation under these conditions is possible. (On the other hand, a high current load will normally require a higher slipping rate and in this way lower the position of the baking zone.)

A reduction of the current to 100 kA (Case B) will lower the baking zone, as shown in Fig. 3. The computed temperatures are considered to be more critical. Use of a lower current load should therefore be followed up by a reduced slipping rate to avoid soft breakage. (However, if the current is reduced until the steel casing has the capacity to conduct all the current, the electrode can be operated with a baking zone below the holder.)

The calculations of current and temperature distributions have been repeated using the three dimensional model ELKEM 3X. Fig. 4 shows cross-sections of an electrode segment. The geometry covers 1/8 of the electrode cross-section with 2 x ½ contact clamps, included 2 bus tubes. Each tube conducts 8.125 kA of the electrode current, as before, a total of 130 kA (Case A). The slipping rate is 0.6 meter/24 h, also as before. The segment is divided into 2310 computational points. The maximum number of gridpoints (3696 in the ELKEM 3X model) and the computer costs explain the relatively simple geometry.

The cross-sectional area selected in Fig. 4 is 0.2 meter above the lower end of the contact clamps. The temperature profiles illustrate conditions during baking where the fins are active conductors of heat and current. The 500°C isotherm requires special attention in this connection, and the effect of current variations are clearly de-

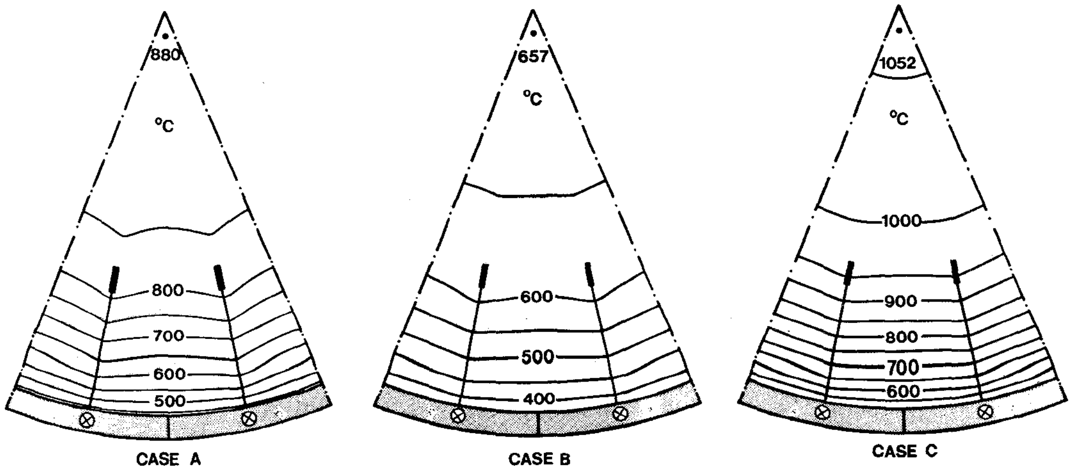

Fig. 4. Temperature distribution in electrode cross-sections. Case A 130 kA, Case B 100 kA, Case C 150 kA.

MATERIAL CHANGES WITH TEMPERATURES

The baking process, where the electrode is "produced", is, as already pointed out, closely connected to the temperatures in the holder region. In this process, the carbon materials are drastically changed, volatile matters are evolved and the paste is transformed to a material of high strength at temperatures of 400°C to 500°C. The volatiles pass downwards in the electrode and are cracked into carbon and hydrogen. The deposited carbon improves the strength.

After the baking, the materials will shrink at temperatures up to 800°C to 1000°C. At higher temperatures the electrode carbon will expand according to the curves in Fig. 5. It is very important for a proper electrode production in the holder region to have these conditions controlled and stabilized. The position of the baking zone, its connection to current variations and the importance of a safe slipping have been discussed.

However, the shape of the zone is also important in regard to material quality. Fig. 3 indicates that normal electrode conditions and a baking zone highest in the electrode center is advantageous for the shrinkage conditions. Regarding thermal stresses, it is also deemed favourable that the isotherms are of approximately the same shape in the holder region as further down in the electrode. A very high position of the zone, as the operation with 150 kA, may, on the other hand be a disadvantage owing to a very hot electrode. In the last case with 100 kA, the shape of the baking zone is somewhat different, but it should not cause any problems regarding the baked materials. However, if the low current is combined with a high slipping rate, the baking zone will be even lower towards the electrode center. The paste shrinkage will take place in various directions, creating abnormal stresses in the materials.

If the current fluctuates considerably, as in the examples (between 100 and 150 kA), and within relatively short time intervals (up to one day), the shape of the baking zone will move accordingly. This is expected to have a strong influence on the quality of the baked carbon materials, again due to the shrinkage in various directions and crack formation.

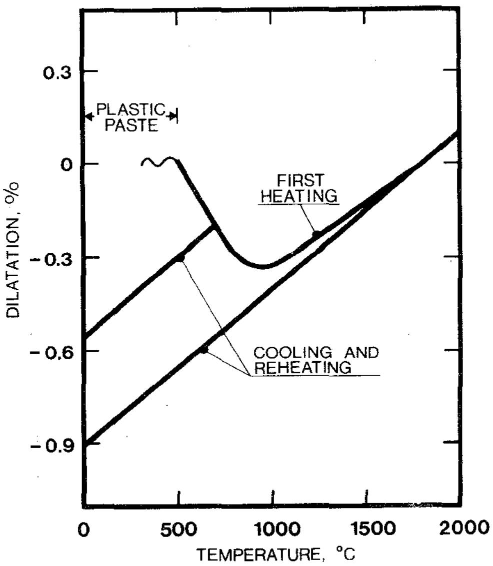

Fig. 5. Dilatation of electrode carbon as a function of temperature.

The solid part of the electrode attains increasingly high temperatures downwards, as illustrated in Fig. 2. Thermal stresses are set up, but in our opinion, during the slow descent these stresses are to a large extent released by structural changes, or it is assumed that during steady state operation the time should be sufficient enough to give a good relaxation of the stresses. It is known that stresses during normal operation very seldom cause breakages.

MATERIAL STRENGTH DURING HEAT CYCLING

The high temperature strength of carbon materials is an important property in order to prevent electrode breakages. The strength is, as for other material properties, temperature dependent. In addition to the actual temperatures, the property also depends on a possible previous heat-treatment to higher temperatures.

In order to achieve reliable measurements of the mechanical properties of electrode samples, we have invested in an advanced testing machine, equipped with a high temperature, high vacuum and controlled atmosphere testing furnace. This equipment makes it possible to determine the mechanical properties at temperatures up to 2000°C.

Fig. 6 shows measured tensile strength of carbon materials as a function of temperature. Before the measurements the paste samples were baked to a maximum temperature of 1000°C. An increase of the mechanical strength will normally take place up to about 1500°C. At higher temperatures, the strength may be different depending on

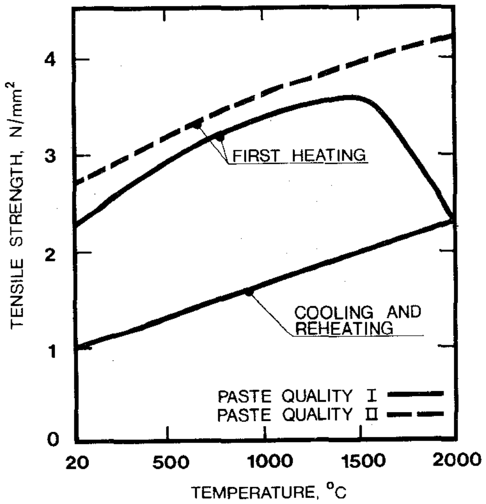

Fig. 6. Tensile strength of electrode carbon as a function of temperature

the carbon raw materials. Examples for two paste qualities are presented in the figure.

Heat treatment above 1500°C will for paste I lead to an irreversible and accellerating degradation of the mechanical strength. By cooling the material after heat-treatment at 1500°C respectively 2000°C, a further degradation of strength was found. A new heat-treatment to 1500°C or 2000°C will, however, lead to an increase of the mechanical strength. In fact, we found that the strength at 1500°C and 2000°C was unchanged after cooling and reheating. The strength at room temperature was also the same after a second heat-treatment.

The decrease of mechanical strength in the temperature range 1500 to 2000°C is irreversible, and is probably caused by the formation of cracks and changes in the pore structure under the first heat treatment at temperatures above about 1500°C.

The reversible changes of strength may be explained by a "frozen in" mechanism. Internal stresses, due to differences in the coefficient of thermal expansion between the coarse anthracite particles and the binder fraction (binder and fines), are frozen during cooling of the material. These internal stresses will be released by reheating (6).

Paste quality II in Fig. 6 shows a higher tensile strength compared with quality I. The property gradually improves up to 2000°C (Measurements during cooling have not been carried out.)

The findings will later in this paper be viewed in relation to electrode operation, including current/heat cycling.

THERMAL STRESSES WITH VARYING CURRENT

Calculated temperatures will only indicate the thermal stresses in an electrode. The mathematical model, ELKEM T, has therefore been developed for computation of these stresses. In this program, temperatures calculated by the dynamic model, Elkem D, as well as temperature-dependent mechanical properties are taken into account.

The main purpose of the model is to simulate stop and restarting procedures in order to avoid hard electrode breakages. In this paper some typical examples will be presented. Cycling of the electrode current has been included.

Stresses during Shut-downs

From time to time the furnace will be stopped due to maintenance work, current cut or other reasons causing shut-down. The current variations may lead to abrupt temperature changes and high thermal stresses. These stresses are closely connected to the length of the cooling period and other operational parameters.

A shut-down procedure, as illustrated in Fig. 7, has been simulated. The normal electrode current at steady state conditions is 130 kA, shown in Case A. In ELKEM D, the current input is further changed according to the curve: a sudden current cut-off, followed by a furnace shut-down of 6 h, after which the current is switched on and immediately increased to full load. In addition, the thermal boundary conditions are input, and varied in accordance with time. The current and temperature distributions at designated time steps are output data.

The corresponding stresses as a function of time are also presented in Fig. 7, but for a certain part of the electrode only. This section is selected from the electrode where the highest thermal stresses, also considered as critical regarding fracture, are calculated. In this case they are found in the electrode center at furnace charge level. (The electrode center starts with compression, which turns to tension at the end of the shut-down period. The stress components in the longitudinal direction are dominating (5)). The resultant stresses are computed according to a fracture criterion. They reach, in Fig. 7, their maximum after approximately 10 h, or some time after a return to normal load.

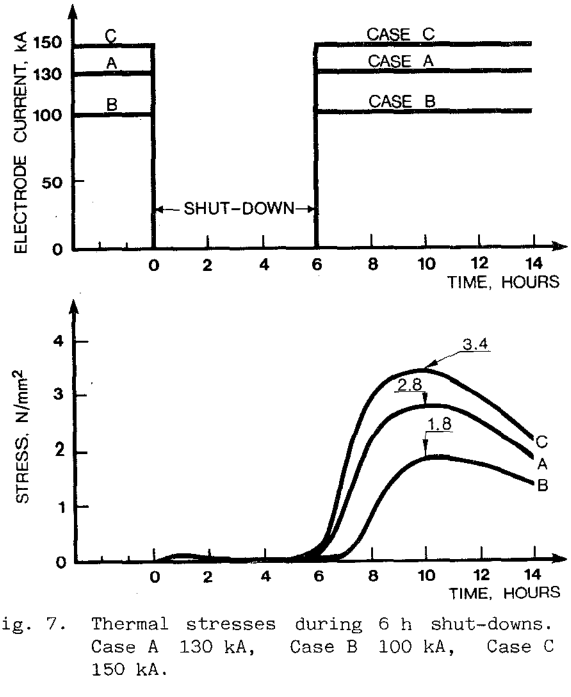

Fig. 7. Thermal stresses during 6 h shut-downs. Case A 130 kA, Case B 100 kA, Case C 150 kA.

The simulation has been repeated in two other cases, with current 100 kA (Case B) and 150 kA (Case C) during stationary operation. The stresses are also presented in Fig. 7, where they are compared to the normal values (Case A). A low current is equivalent to a less hot electrode before the shut-down, causing considerably lower stresses to occur. Many of the hard breakages are related to a very hot electrode. Therefore, by using a high current load, it is recommended that the current should be reduced 10 to 20 per cent during a period of 1 to 2 days before a planned, long shut-down. In this way, it is possible to produce a new and colder electrode before the current is switched off.

Based on a series of previous calculations, recommended shut-down procedures for electrode operation have been worked out. A summary of the calculations where current is involved should be of interest in this connection (5):

- The furnace shut-down time is of main importance. A 3 to 4 h stop will, like stationary operation, normally not cause any serious problems. A prolonged shut-down period gives an unfavourable increase of tensile stresses, owing to the greater temperature changes compared with stationary conditions.

- The current reduction time, before the load is switched off, means an increase of the stresses owing to the prolonged cooling period.

- The current recovery time should, during a relatively short current cut, for example 6 h, be raised to normal load as soon as possible. This means reduced stresses. However, during longer shut-downs, for example 12 h, a long current reduction and a correspondingly long recovery time is, in most cases, found as an advantage.

Stresses during Repeated Shut-downs

The current load has in some furnaces to be considerably reduced or completely cut-off during certain periods of the day, the reason being the local power supply. Problems with electrodes have occurred even if the current reduction has been of a relatively short time. This cycling of the process is of interest to simulate.

Fig. 8 shows a sudden current cut-off, followed by a furnace stop of 3 h, and a momentary increase to full load, 130 kA. In this case, however, a similar stop is repeated after 21 h normal operation. During this period the electrode has a normal slipping procedure (525 mm total).

The stress variations in relation to time for a certain part of the electrode are illustrated in the same figure. (As before, the resultant stresses are dominated by the tensile stress component, and are found in the center part of the electrode). As seen in Fig. 8, the resultant stresses will be lower than in the above cases. On the other hand, they will be somewhat higher during the second cycle. The following should be noted if such a procedure is to be used: Small cracks in the carbon materials may occur in connection with the first stop, which during repeated cooling and heating can propagate - the worst case being - to a broken electrode. The risk will increase if the weak electrode part obtains an unconvenient position in the furnace during a new and perhaps longer shut-down.

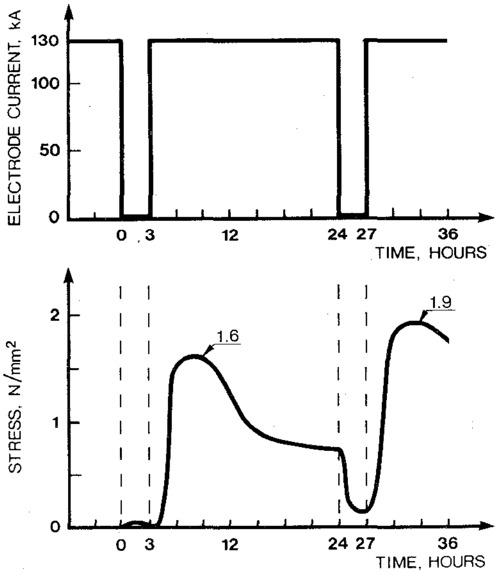

Fig. 8. Thermal stresses during repeated, short shut-downs.

The stationary stress conditions are used as reference stresses in all the reported simulations. These are very small, and only the weight of the electrode is taken into account. It is assumed that the duration of steady state operation allows sufficient time for good relaxation of the stresses. Stresses have also been calculated with the thermal conditions before the second shut down in Fig. 8 as the reference. Any significant difference compared with the presented results has not been found.

Stresses during Current Fluctuations

Fig. 9 shows a simulation of current variations between 100 kA and 150 kA, from 130 kA as normal condition. Similar fluctuations are reported from normal operating furnaces during tapping cycles. Various types of electrode problems have been experienced in this connection.

The resultant thermal stresses will vary with time as shown in the same figure. The highest stresses are in this case found just below the electrode holder and towards the surface - but the actual material has been slipped 0.6 meter during the 24 h simulation. (Tension in the longitudinal direction is still dominating, but radial tensile stresses are of approximately the same size.) Fig. 9 also includes a curve showing stresses in the electrode center at the charge level. This normally very critical part of the electrode, has considerably lower stresses.

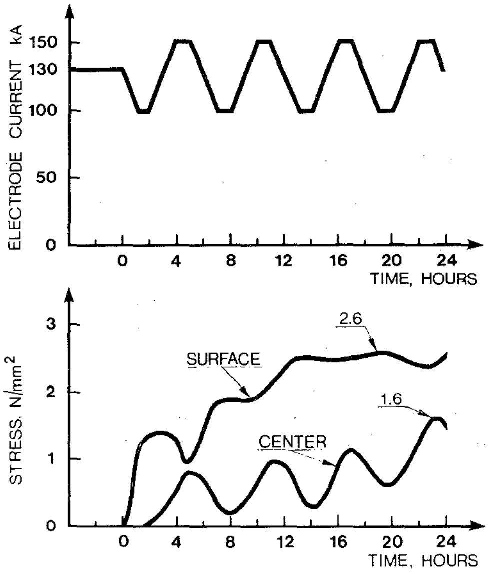

Fig. 9. Thermal stresses during current fluctuations.

The computed stresses caused by the first current cycle are low compared with stresses due to shut-downs. When the procedure is repeated several times, relatively large stresses are computed.

Stresses Compared with Measured Strength

The effect of current variations in industrial operation is similar to the heat treatment procedure in the high temperature furnace. The tensile strength data from the laboratory measurements have therefore been used to compare some of the model simulations.

The calculated resultant stresses from a shut-down (Fig. 7, Case A) have been compared with the tensile strength in Fig. 6. This is presented in Fig. 10, where stresses above 100 per cent mean fracture of the electrode materials. As seen, there are great differences in the fracture margin if the following paste qualities are used (from the left to the right in the figure):

- The first heating of paste quality I
- The cooling/reheating of paste quality I
- The first heating of paste quality II

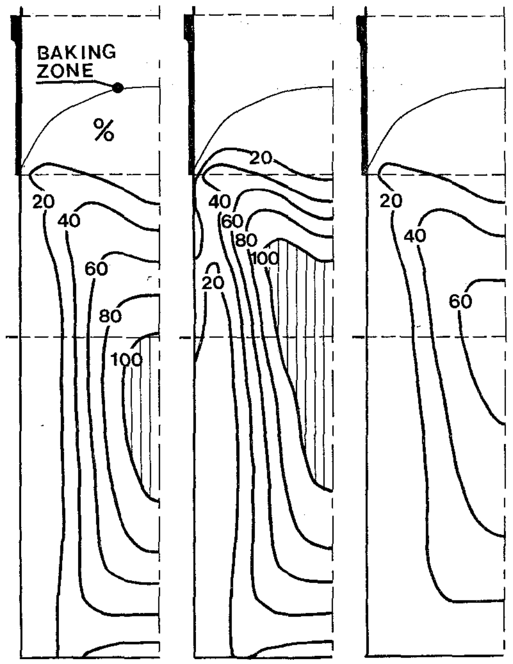

Fig. 10. Calculated thermal stresses compared with measured tensile strength.

CONCLUDING REMARKS

This paper presents some new computations with our mathematical electrode models. Interesting results have been obtained regarding thermal stresses in relationship to variations of electrode current. Heat cycling in laboratory furnaces shows great material changes for electrode carbon. The results indicate that repeated current reductions will increase the tendency for an unsafe electrode operation.

It should be noted that more uncertain computations are expected when the simulating time is being increased. This is connected to the selection of reference stresses, but also owing to the mechanical properties. These are temperature dependent in the model, but difficult to measure during repeated heat treatment. Determining the modulus of elasticity above 1000°C is particularly difficult.

Furthermore, the results show that it is important to produce electrode carbon which can resist high thermal stresses. We will continue laboratory testing at high temperatures, including new techniques as methods for thermal shock resistance, calculating micro stresses in composite materials, image analyses and fractography.

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